Enabling R&D Budget Summary

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Virtual Laboratory for Technology

OFES Budget Planning Meeting
March 18, 2003

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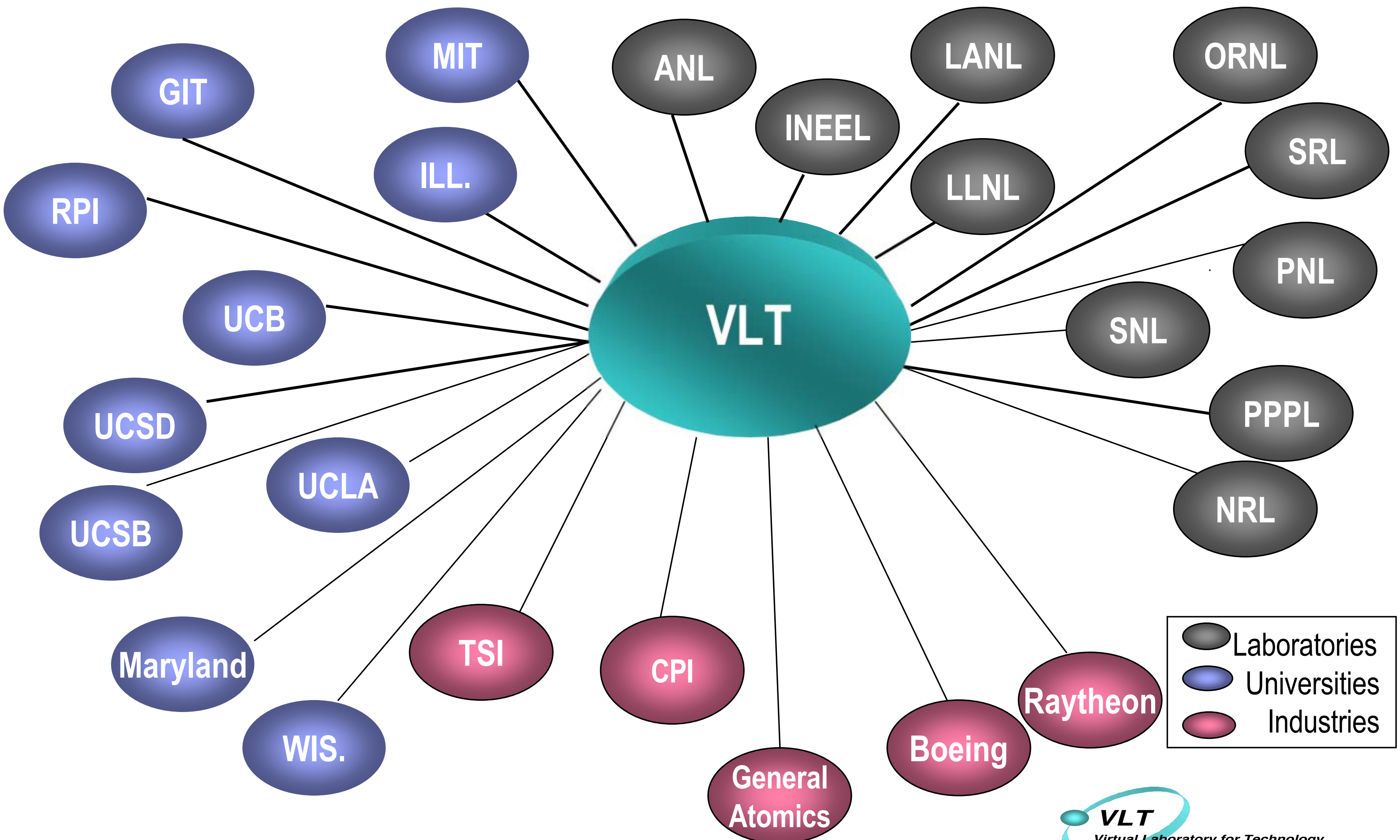
For Fusion Energy Science

The Enabling Technology Research Mission

To contribute to the national science and technology base by developing the enabling technology for existing and next-step experimental devices, by exploring and understanding key materials and technology feasibility issues for attractive fusion power sources, by conducting advanced design studies that integrate the wealth of our understanding to guide R&D priorities and by developing design solutions for next-step and future devices.

The Technology Program is a Multi-institutional National Resource



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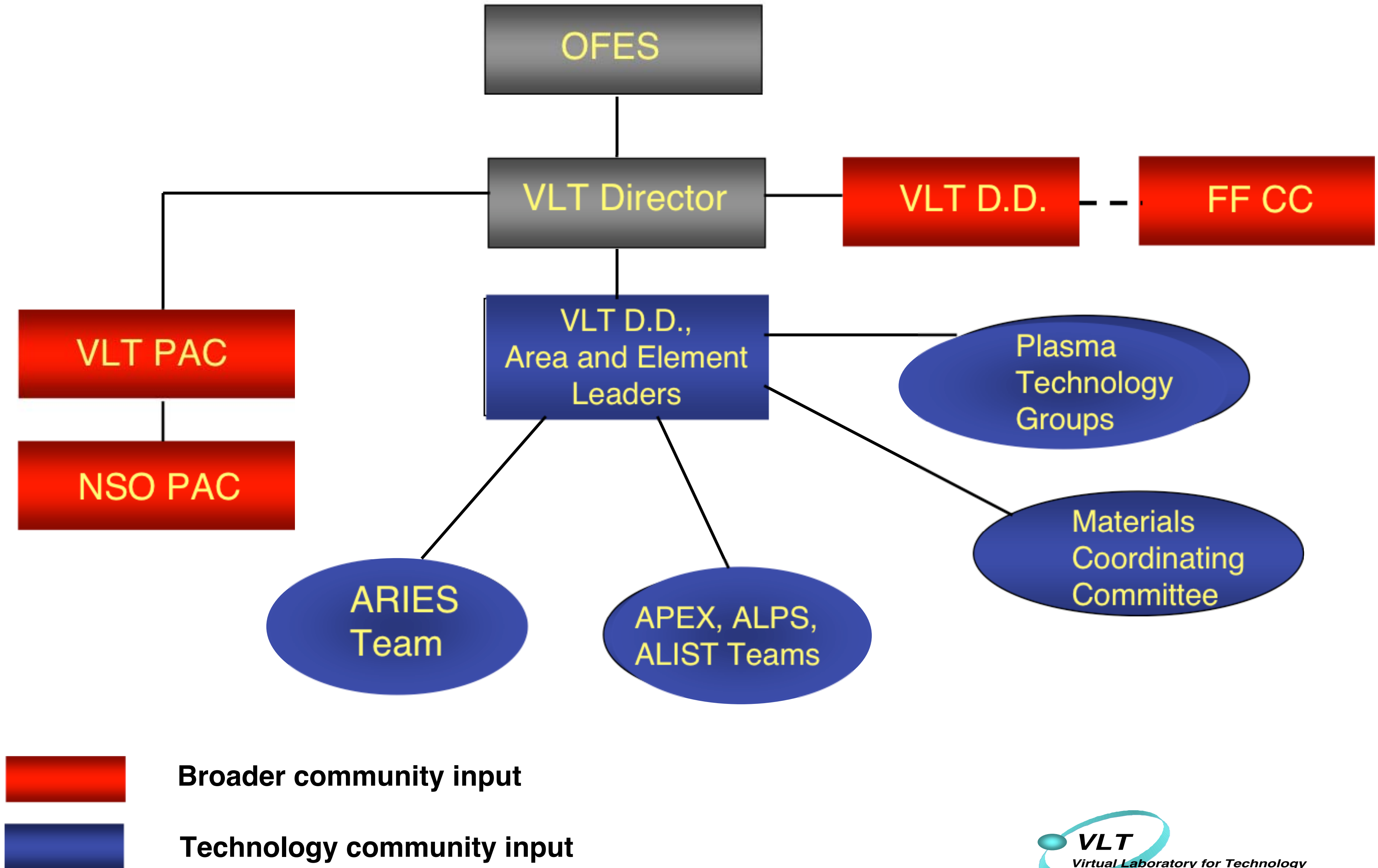
VLT Governance Overveiw



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VLT Program Advisory Committee Members

PAC Member	Service Completed at End of Year
J. Freidberg, Chair	2005
D. Batchelor	2003
J. Dahlburg	2004
R. Hawryluk	2004
B. Hooper	2004
T. Jarboe	2003
J. Kwan	2004
P. Peterson	2005
J. Sethian	2003

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VLT PAC Comments

- **The proposed FY2004 budget allocations upset the balance needed to meet the mission of the Fusion Energy Sciences Program. The most striking feature of the problem is the devastating cuts to technology.**

- **Program balance is needed to develop attractive fusion energy on the time scale called for by President Bush. The challenges facing development of an attractive fusion power source lie as much in fusion technology as in plasma science.**
  - ***Curtailing systems studies reduces an activity that has been proven highly beneficial in guiding fusion research.***
  - ***Elimination of thick, liquid wall chamber work effectively stops a key component in the development of a major IFE path.***
  - ***Terminating MFE chamber technology undermines the ability to demonstrate the principles of tritium fuel self-sufficiency as well as reliable heat extraction at high temperatures.***
  - ***Stopping work on FIRE eliminates the only US burning plasma option other than ITER.***

- **Under the proposed 2004 budget a number of highly skilled members of the fusion engineering community will be driven from the program. It will remove key people that the US needs to keep in the program during the negotiation, design, and construction phases of ITER.**

- **An equally important serious issue with the 2004 budget, and potentially the 2005 budget as well, is that only $2M has been allocated for direct ITER support.**

VLT Program Area Coordinators and Element Leaders

Program Element	Element Leader
Plasma Technologies – (S. Milora, Coordinator)	
Magnets	J. Minervini
PFC	M. Ulrickson
ICH	D. Swain
ECH	R. Temkin
Fueling	S. Combs
Fusion Technologies – (M. Abdou, Coordinator)	
Chamber	M. Abdou
Safety (MFE & IFE)	D. Petti
Tritium - TSTA	S. Willms
Tritium - Research	D. Petti
Remote Handling	M. Menon
Advanced Design – (F. Najmabadi, Coordinator)	
NSO	D. Meade
ARIES	F. Najmabadi
Socio-Economic	J. Schmidt
Materials – (S. Zinkle, Coordinator)	
Materials	S. Zinkle
IFE Technologies – (W. Meier, Coordinator)	
Chamber	W. Meier

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Enabling R&D Program Budgets ($K)

Program Area	Program Elements	FY03 Feb	FY 04 CBR	FY 04 VLT Planning
Plasma Technologies	Plasma Facing Components	6506	6254	6254
Plasma Technologies	MFE Magnets	2073	2164	2164
Plasma Technologies	ICH and RF Systems	1623	1334	1334
Plasma Technologies	ECH and Gyrotrons	1128	1185	1185
Plasma Technologies	Fueling	913	930	930
Plasma Technologies	Neutral Beams	64	60	60
Plasma Technologies	Safety and Environment*	0	1325	1325
Plasma Technologies	Tritium Research*	0	608	608
Plasma Technologies	Neutronics*	0	75	75
Plasma Technologies	Taxes		51	51
Plasma Technologies	**TOTAL**	**12307**	**13986**	**13986**
	* Moved from Fusion Tech. in FY 04			
Fusion Technologies	TSTA	2917	0	0
Fusion Technologies	MFE Chamber Technologies	2980	840	3024
Fusion Technologies	*IFE Chamber Technologies*	*2216*	*498*	*2216*
Fusion Technologies	MFE Safety and Environment	1310	0	0
Fusion Technologies	*IFE Target Fabrication***	*690*	0	0
Fusion Technologies	Tritium Research	605	0	0
Fusion Technologies	*IFE Safety and Environment*	*308*	*0*	*308*
Fusion Technologies	Remote Systems	110	0	110
Fusion Technologies	**TOTAL**	**11136**	**1338**	**5658**
	**Funded by Research Division prior to FY 03			
Advanced Design	Next Step Option	1901	0	1901
Advanced Design	*IFE System Studies*	*1005*	0	
				> 2064
Advanced Design	MFE System Studies	1060	1366	
Advanced Design	VLT Management	774	504	504
Advanced Design	Socio-economic Studies	217	0	148
Advanced Design	Technology Awards	395	0	0
Advanced Design	Burning Plasma Applications	179	120	120
Advanced Design	ITER Cost Estimating	520	0	0
Advanced Design	**TOTAL**	**6051**	**1990**	**4737**
Materials Research	**Materials Science**	**7647**	**7600**	**7600**
Enabling R&D	**TOTAL**	**37141**	**24914**	
	TOTAL MFE	**32922**	**24416**	
	TOTAL IFE	***4219***	***498***	

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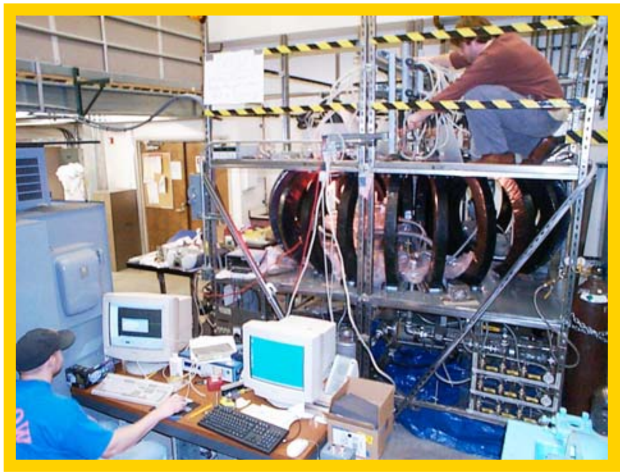
Chamber Technology Achievements in FY02/03

- **Facilities were constructed and operated to address liquid breeder MHD in both free-surface and closed channels.**
- **Sophisticated and complex computer code development is underway for 3-D modeling of fluid flow.**
- **Established a temperature window in which a liquid wall can operate within an MFE reactor with a high exit coolant temperature for power conversion.**
- **Explored advanced solid wall blanket concept with potential to improve the attractiveness of fusion power plants.**
- **Obtained experimental results of the effective thermal properties of beryllium packed beds.**



MTOR allows experiments on MHD fluid flow in self-cooled liquid metals, and free-surface liquid walls.

FLIHY addresses key issues and innovative techniques for enhancing heat transfer in low-conductivity fluids in closed channel flows.

VLT FY02/03 Accomplishments and FY04/05 Deliverables

MFE Chamber Technologies

Program Element	FY02/03 Accomplishments	FY04/05 Deliverables
• **MFE Chamber Technologies**	• Facilities were constructed and operated to address liquid breeder MHD in both free-surface and closed channels (UCLA). - MTOR, for experiments on MHD flow - FLIHY, for low conductivity liquids. • Computer code development for 3-D MHD modeling of fluid flow. • Established a temperature window in which a liquid wall can operate within an MFE reactor with a high exit coolant temperature for power conversion. • Joint effort between APEX and ALPS advanced R&D and design activities to put a liquid surface test module in NSTX and supported modeling of Li-DiMES experiment in DIII-D. • Explored advanced solid wall blanket concepts with potential to improve the attractiveness of fusion power plants. • Experimental results of the effective thermal properties of beryllium packed beds.	• Complete MHD assessment on the liquid metal free surface module options for near term experimental devices such as NSTX. (09/04) • Start the process of selecting ITER blanket test module candidates. (01/04) • Participate in IEA activities to improve US predictive capabilities in key areas of chamber technology. (10/03) • Complete selection of two primary blanket concepts for testing in ITER based on results of R&D and technical evaluation. (06/05) • Complete engineering design of flowing liquid metal modules for NSTX device. (09/05) • Complete conceptual design of in-pile functional test mock-up for SB/Be thermomechanics. (09/05)

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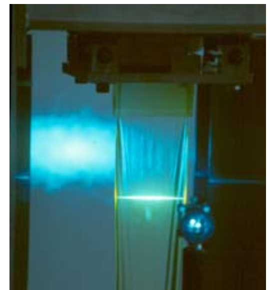
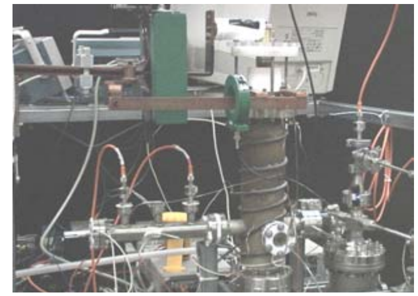
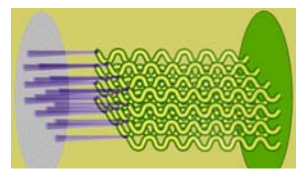
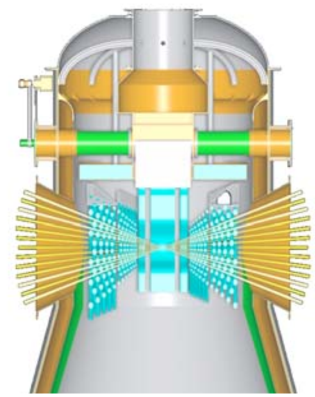
Working closely with heavy ion driver and target physics groups, members of the IFE VLT played key roles in developing the Updated Point Design for HIF and are conducting research on key feasibility issues

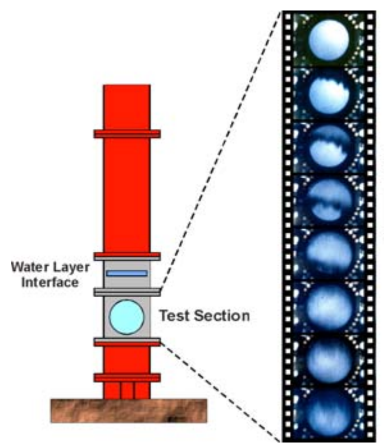
- Liquid jets experiments to demonstrate ability to create protective thick-liquid-wall configuration.
- Condensation modeling and experiments to demonstate ability to operate at high rep-rate.
- Target fabrication techniques, facility layout and costing for power plant target factory.
- Final focus magnet shielding for long life, consistent with beam focusing and target illumination requirements.
- S&E analyses to provide guidance to target designers on choice of holraum materials.
- Systems modeling and integration of driver, chamber and target for self-consistent design.


Surface ripple characterization

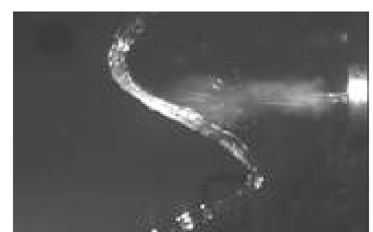

Condensation experiment


Target fabrication


Chamber design



Shocks on liquid layer


Jet array disruption

VLT FY02/03 Accomplishments and FY04/05 Deliverables

IFE Technologies

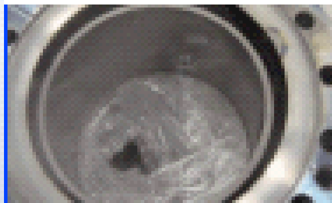
Program Element	FY02/03 Accomplishments	FY04/05 Deliverables
• **IFE Technologies**	• Demonstrated and quantified impact of initial conditions, including flow blockage, for liquid jets needed for thick liquid protection of IFE chamber first walls. • A new test section was designed and built for a vertical shock tube to study pressure response and liquid breakup in support of IFE chamber technology. • Developed updated configuration for heavy ion driver interface with chamber, including mechanical design and shielding analysis. • Determined experimentally-verified laser-induced damage threshold (LIDT) in Al, Cu, and SiC reflective optics. • Completed design and assembled experimental target injection system for single-shot operation and made first shots. • Completed plant layout and costing study for mass-produced IFE targets (both direct and indirect drive).	• Improve state of the art in modeling and experimental exploration of post-shot chamber dynamics and clearing. (09/04) • Modify jet disruption experiments to use high explosives and conduct experiments. (01/04) • Incorporate latest liquid safety findings and address chemical hazards for HIF. (09/04) • Continue single-shot testing with experimental target injection and tracking system and upgrade to rep-rated (6 Hz) capability. (09/04) • Complete evaluation of target fabrication facilities, including interaction with target designers and target fabrication specialists. (03/05) • Report results on multi-scale modeling of pulsed radiation damage in IFE structures. (09/05)

INEEL

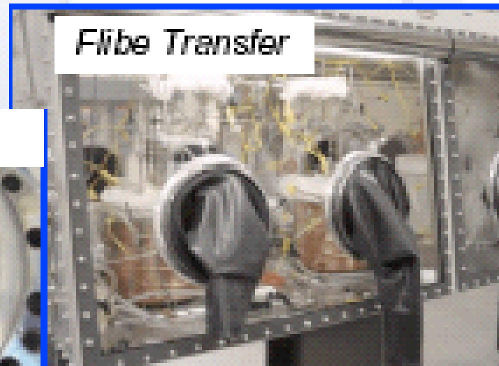
Safety and Tritium Applied Research (STAR) Facility & Molten Salt Experiments

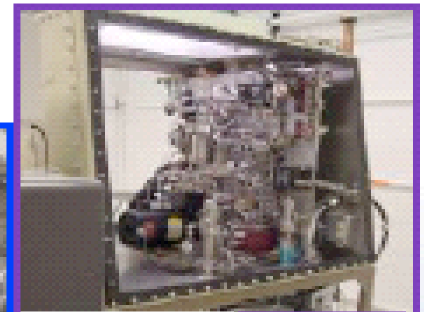
- STAR Tritium Infrastructure being installed
- Tritium Plasma Experiment (TPE) being installed in STAR
- Flibe manufacturing and purification capability developed at INEEL
- Flibe experiments to understand tritium behavior, mobilization and REDOX control are underway this year as part of JUPITER-II collaboration.

High Purify Flibe

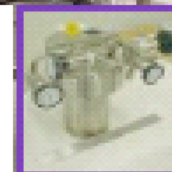


Flibe Transfer

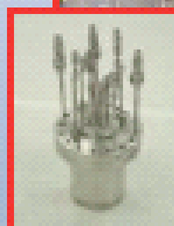




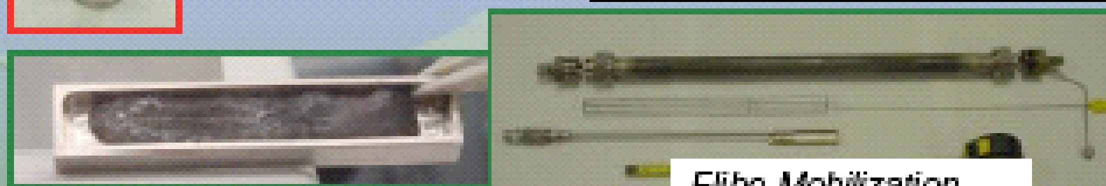
Tritium Storage and Assay System



Flibe Tritium Permeation Expt



Flibe Purification & REDOX



Flibe Mobilization

VLT FY02/03 Accomplishments and FY04/05 Deliverables

MFE/IFE Safety & Environment and Tritium Research

Program Element	FY02/03 Accomplishments	FY04/05 Deliverables
• **MFE/IFE Safety & Environment and Tritium Research**	• STAR refurbished for use by fusion program and JUPITER-II collaboration. • Disassembled (at LANL) and reassembled the Tritium Plasma Experiment (TPE) in STAR (at INEEL). • Demonstrated purification of Flibe molten salt, completed first series of tritium experiments in molten salt Flibe, and completed first series of molten salt mobilization experiments. • Performed screening safety analysis of liquid wall concepts in APEX.	• Complete first series of molten salt REDOX experiments. (12/03) • Complete safety and environmental assessment of ARIES Compact Stellarator study. (09/04) • Complete first series of experiments on tritium behavior in ITER relevant material using TPE to study potential co-deposition. (09/04) • Complete tritium experiments on REDOX controlled Flibe. (09/05) • Begin long-term corrosion experiments using REDOX controlled Flibe. (02/05) • Complete tokamak dust experiments in support of ITER. (08/05)

VLT FY02/03 Accomplishments and FY04/05 Deliverables

Remote Systems

Program Element	FY02/03 Accomplishments	FY04/05 Deliverables
• **Remote Systems**	• Precision mapping of plasma facing surfaces in NSTX. • Range measurement on melting lithium puddles inside CDX-U through a vacuum window.	• Evaluate the usefulness of the FM CLR diagnostic technique for studying the behavior of liquid metal modules in fusion experiments. (09/05)

Major FIRE Accomplishments (Feb 02 - Feb 03)

FIRE Simulation
US Fusion Simulation Project

- Snowmass Assessment confirmed FIRE design basis.
- FESAC found FIRE to be attractive option for BP experiment , and recommended Dual Path Strategy.
- Design space expanded for ARIES-like AT mode with Q = 5, β_N ~4, f_{bs}~80%and > 95% J(r) equilibration.
- FIRE-Based Development Path presented at Snowmass, FESAC and NRC.
- FIRE design point being updated in response to community input.
- Community reviews identified additional technical work required.

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VLT FY02/03 Accomplishments and FY04/05 Deliverables

Next Step Options - FIRE

Program Element	FY02/03 Accomplishments	FY04/05 Deliverables
• **Next Step Options – FIRE**	• Baseline physics, engineering and costing of FIRE validated at Snowmass. • "Steady-state high-beta" advanced tokamak scenario developed for FIRE. • Complete preconceptual design of divertor and first wall, feasibility of internal RWM coils. • Physics Validation Review, end of FY03.	• Demonstrate feasibility of one ARIES-like AT Scenario for FIRE and ITER RWM stability and feasibility analysis with compatible PFCs. (09/04) • Join ITER Construction Project or begin FIRE Conceptual design. (09/05)

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ARIES-IFE has identified key mechanisms that impact the design window for liquid-wall IFE chambers

- Dimensionless design windows for formation and stability of thin-liquid protection have been produced.
- Mechanism for ablation of liquid protection such as explosive boiling are identified and/or better characterized.
  - ✓ Showed analogy with laser/material ablation (fusion research can benefit from extensive work in this area).
- Condition of chamber prior to each shot is heavily influenced by aerosol formation, concentration, and transport as opposed to droplets. This is a critical issue for both thin- and thick-liquid wall concepts.
- Significant effort has been devoted in exploring various modes of heavy-ion beam transport in the chamber:
  - ✓ Neutralized ballistic transport (1 mTorr)
  - ✓ Self-pinched transport (100 mTorr)
  - ✓ Channel transport (1 Torr)

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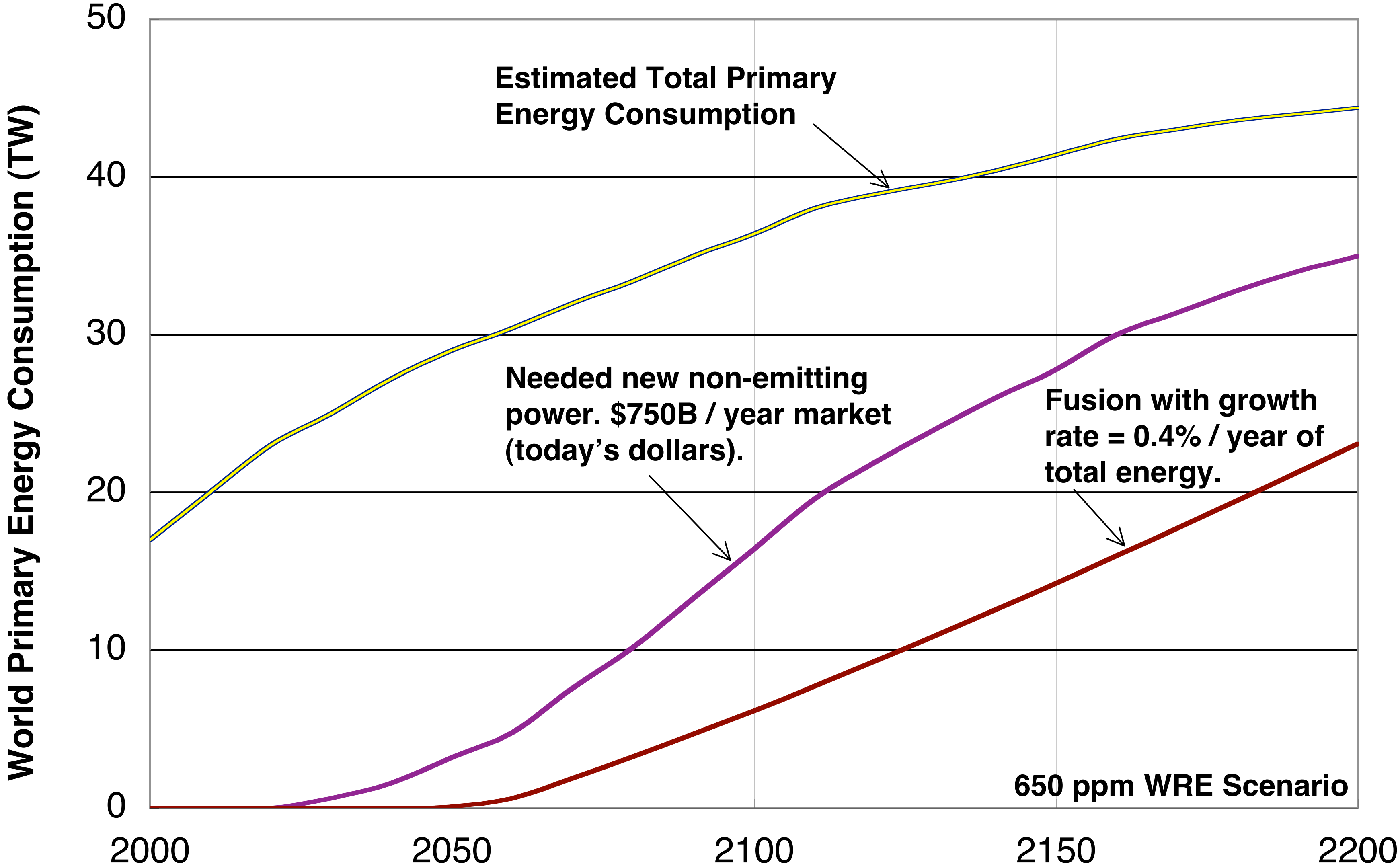
VLT FY02/03 Accomplishments and FY04/05 Deliverables

System Studies and Socio-economic Studies

Program Element	FY02/03 Accomplishments	FY04/05 Deliverables
• **System Studies**	• Completion of ARIES-IFE study, assessment of IFE power plant assessment with emphasis on innovation and evaluation of chambers and chamber interfaces with the driver and target systems. • The results from ARIES-IFE study in a special issue of Fusion Science and Technology. • Initiation of ARIES compact Stellarator study.	• ARIES Compact Stellarator Study – development of compact stellarator coil/plasma configuration tools. (09/04) • ARIES Compact Stellarator Study – exploration of configuration design space. (09/05)
• **Socio-economic Studies**	• Analyzed the future market for hydrogen, with and without climate policies, including fusion electrolysis within the portfolio of potential production technologies. • Developed a time-of-day electricity-pricing model suitable for modeling the production of hydrogen from large-scale fusion reactors in macro-economic market models. • Developed a scenario for world wide deployment of fusion energy that found use at high levels in DOE.	• Publish an analysis, in collaboration with the Global Technology Strategy Program (GTSP), of fusion technology deployment considering competitive market and government policy driven opportunities within the advanced technology portfolios that could evolve during the 21st century. (09/04) • Develop US fusion deployment scenarios that are consistent with the world deployment scenarios established in FY03. (04/04) • Publish a comprehensive analysis of fusion's competitive position/synergies with other advanced energy technologies. (09/05)

Fusion will Contribute on a Timely Basis



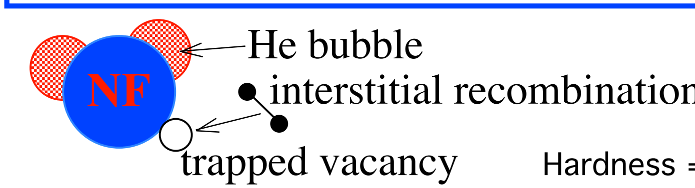
World population growth will be in cities and "megacities," requiring large new power stations.

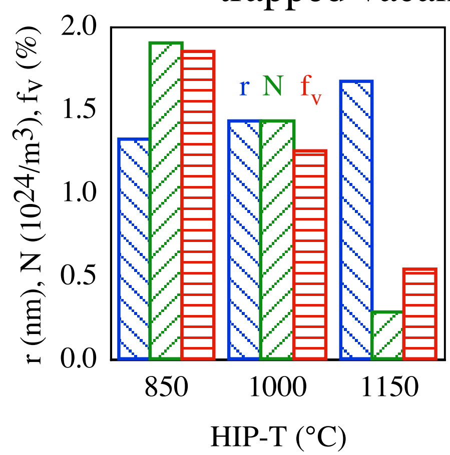
Substantial Progress has occurred in Nanocomposited Ferritics (NCFs)

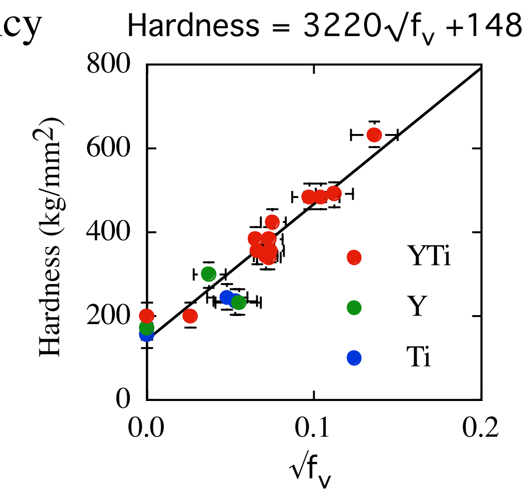
- Key steps in the processing path to create NCs have been identified
  - Showed that NCs precipitate during high-T consolidation
  - Evaluated effects of key variables on NCs - milling energy, consolidation (HIP-T) & Ti
  - Ti and Y are essential for producing fine-scale NCs (otherwise coarse Y_2O_3 and TiO_2 particles, respectively)
- Contribution of NCs on strengthening has been quantified
- Fundamental knowledge base for alloy design and modeling is now in place
- Created wide range of NCs/sink structures to study He effects - partitioning, trapping & management in HFIR
- Many challenges still remain
  - toughness enhancement, fabrication, costs, ...

Key to outstanding potential of NCFs - high number of < ≈ 3nm Y-Ti-O nano-clusters (NCs)

- high creep strength
- trap-distribute He
- recombine vacancy-interstitials







Develop/apply state-of-the art tools: 3D-AP, SANS (new), Z-contrast TEM, …

UCSB / ORNL / PNNL collaboration

VLT FY02/03 Accomplishments and FY04/05 Deliverables

Materials Science

Program Element	FY02/03 Accomplishments	FY04/05 Deliverables
• **Materials Science**	• Multi-scale computational research, including molecular dynamics and 3-D dislocation dynamics, has been coupled with detailed experimental studies to investigate the physical mechanisms responsible for flow localization in metals irradiated at low temperatures. • A comprehensive investigation of mechanical deformation mechanisms in unirradiated and irradiated vanadium alloys was completed (OMB FY02 milestone). • The nonoscale features responsible for the outstanding mechanical properties of nanocomposited ferritic steel have been quantitatively evaluated. Evidence for new thermodynamic processes at the nanoscale have been obtained. • A science-based program has led to the development of SiC/SiC composites with good resistance to radiation-induced mechanical property degradation up to ~10 dpa. • Static capsule compatibility experiments for candidate V/Li MHD insulators have identified several candidates which may perform satisfactorily for temperatures up to 800˚C.	• Complete first round of detailed comparison of computational (molecular dynamics) and experimental studies on the interaction between moving dislocations and dislocation loops, bubbles, voids, defect clusters and precipitates responsible for hardening, embrittlement and plastic flow localization in alloys. (04/04) • Complete analysis of the physical origins of the superior mechanical properties of nanocomposited ferritic steels, and make a preliminary assessment of the influence of nanoscale features on thermodynamics. (12/03) • As part of the JUPITER-II program, evaluate the irradiation behavior of new SiC/SiC composites possessing low gas permeability, high strength, high toughness, and high thermal conductivity. (08/04) • Complete investigation of the thermodynamics, interface structure, irradiation stability and helium trapping efficiency of the nanometer yttrium-titanium based oxide dispersoids in nano-composited ferritic alloys. (12/04) • Determine the effect of helium additions on the low temperature radiation embrittlement of ferritic-martensitic steels, as part of the DOE/JAERI program and modeling initiative. (07/05) • Provide critical engineering validation data and engineering design support for the IFMIF ion source, accelerator, target system, and test cell. (08/05)

Principal VLT Milestones for FY04/05

Proposed OFES Major Milestones for FY05 (in red)

Program Element	Principal Milestones - FY04	Principal Milestones - FY05
• Plasma Facing Components	• Complete MHD testing of free surface Li liquid flow in NSTX magnetic fields with externally applied currents. (09/04) • Determine, through controlled experiments, hydrogen isotope adsorption/desorption properties of liquid metal materials proposed for use in ALPS components (Li, Ga, and Sn). Ion impact desorption cross sections will be measured to quantify recycling rates during plasma exposure. (06/04) • Carry out studies of redeposited carbonaceous films generated by beryllium seeded plasmas. (09/04)	• Initiate R&D effort to support US role in ITER PFC fabrication. (06/05) • Conduct final MHD tests in preparation for NSTX liquid module. (09/05) • Complete studies of tungsten beryllium mixed material layer formation and redeposition in PISCES-B and SNL-TPE. (09/05)
• MFE Magnets	• Test of the CICC samples in the SULTAN Facility. Analyze data and issue test report indicating impact on modified ITER Design Criteria. (04/04)	• Testing of the mixed strands CICC in SULTAN. (01/05)
• ICH and RF Systems	• Complete testing of JET High-Power Prototype antenna; deliver report. (10/03)	• Complete fabrication of advanced antenna for ET. (03/05)
• ECH and Gyrotrons	• Complete fabrication of 110 GHz, 1.5 MW industrial gyrotron at CPI. (03/04)	• Complete testing of 1.5 MW, 110 GHz gyrotron with a two-stage depressed collector. (03/05)

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Principal VLT Milestones for FY04/05 (cont'd)

Proposed OFES Major Milestones for FY05 (in red)

• **Fueling**	• Characterization of pellet survivability and gas loading with pumped curved guide tube. (06/04)	• Complete construction of twin-screw extruder relevant for long-pulse burning plasma. (09/05)
• **MFE Chamber Technologies**	• Complete MHD assessment on the liquid metal free surface module options for near term experimental devices such as NSTX. (09/04)	• Complete selection of two primary blanket concepts for testing in ITER based on results of R&D and technical evaluation. (06/05)
• **IFE Chamber Technologies**	• Improve state of the art in modeling and experimental exploration of post-shot chamber dynamics and clearing. (9/04)	• Complete evaluation of target fabrication facilities, including interaction with target designers and target fabrication specialists. (3/05)
• **MFE & IFE Safety and Environment; Tritium Research**	• Complete first series of molten salt REDOX experiments. (12/03)	• Complete tritium experiments on REDOX controlled Flibe. (09/05)
• **Remote Systems**	• Evaluate the usefulness of the FM CLR diagnostic technique for studying the behavior of liquid metal modules in fusion experiments. (09/04)	• Apply the FM CLR diagnostic technique in experiments involving liquid metal modules. (09/05)
• **Next Step Options**	• Demonstrate feasibility of one ARIES-like AT Scenario for FIRE and ITER RWM stability and feasibility analysis with compatible PFC's. (09/04)	• Join ITER Construction Projector or begin FIRE Conceptual design. (09/05)

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Principal VLT Milestones for FY04/05 (cont'd)

Proposed OFES Major Milestones for FY05 (in red)

• **System Studies (ARIES)**	• Development of compact stellarator coil/plasma configuration tools. (09/04)	• Exploration of compact stellarator. (09/05)
• **Socio-economic Studies**	• Publish an analysis of fusion technology deployment considering competitive market and government policy driven opportunities. (09/04) • Develop U.S. fusion deployment scenarios that are consistent with the world deployment scenarios established in FY 03. (04/04)	• Publish a comprehensive analysis of fusion's competitive position/synergies with other advanced energy technologies. (09/05)
• **Materials Science**	• Complete first round of detailed comparison of computational (molecular dynamics) and experimental studies on the interaction between moving dislocations and dislocation loops, bubbles, voids, defect clusters and precipitates responsible for hardening, embrittlement and plastic flow localization in alloys. (04/04) • Complete analysis of the physical origins of the superior mechanical properties of nanocomposited ferritic steels, and make a preliminary assessment of the influence of nanoscale features on thermodynamics. (12/03) • As part of the Jupiter-II program, evaluate the irradiation behavior of new SiC/SiC composites. (08/04)	• Complete investigation of the thermodynamics, interface structure, irradiation stability and helium trapping efficiency of the nanometer yttrium-titanium based oxide dispersoids in nano-composited ferritic alloys. (12/04) • Determine the effect of helium additions on the low temperature radiation embrittlement of ferritic-martensitic steels, as part of the DOE/JAERI program and modeling initiative. (07/05) • Provide critical engineering validation data and engineering design support for the IFMIF ion source, accelerator, target system, and test cell. (08/05)

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FY04 Funding Issues

	Need
• **Restore funds for MFE chamber & IFE chamber/safety research (2.5/2.1) - *assume keep closeout funds of $1.3M***	**$4.6M**
• **Restore funds for advanced design activities (1)**	**$0.9M**
• **Plasma technology needs - *(PFC, ICH)***	**$0.5M**
• **VLT reserve funds**	**$0.4M**
	$6.4M

Notes

(1) FIRE design work needs to continue in FY04 as part of burning plasma activities ($1M-$2M)

FY05 VLT Initiatives

- Participate in engineering validation/engineering design activity of IFMIF. ($ 3M)
- Begin design and assessment studies for options for a Component Test Facility. ($ 2M)
- Strengthen technology research in key areas to support ITER project tasks *(see Sauthoff's presentation)*
  - plasma heating/fueling systems ($ 4M)
  - plasma facing components ($ 2M)
  - superconducting magnets ($ 2M)
  - blanket test program ($ 2M)

→ Specific needs will evolve as ITER negotiations proceed.

→ Will need investment in upgraded, new test stands.

→ Estimated required funding: $10M

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